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Penetration of a magnetic field in a regular indium wireframe

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Introduction

Studies of superconductors in confined geometries of various types are known since mid 60s [1] when the free space in a porous glass was used to restrain the size of metal grains. In contrast with granular superconductors prepared by e.g. co-evaporation with dielectric, where at least 60% filling fraction is mandatory to complete the percolation path, in porous dielectrics the volume fraction of metal can be made less than 10% with a dc conductivity of a metal type.

Opal is one example of a crystalline porous template — a face centred cubic (FCC) package of identical silica spheres [2] with empty interstitials, which are available for in-filling with a superconductor. The important feature of thus formed ensemble of nanograins is the replacement of unstable intergrain point contacts of granular superconductors with continuous bridges connecting adjacent nanoparticles. In the opal-based nanocomposites the size and spacing of nanostructures are identical throughout the array within 5–10% deviation.

Early experiments made on In nanograins embedded in opal have shown the very unusual behaviour of the critical current and magnetoresistance [3, 4]. Here we discuss the alteration of critical parameters of the In-opal nanocomposite with the progressively reduced filling fraction of In from 26% to 8%.

1. Experimental results and discussion

Opals in use consist of silica spheres with diameter $D = 234$ nm. In accord with the void geometry there are alternated O-grains with characteristic size $d_O = 0.41D$ connected each with T-grains of $d_T = 0.23D$ via bridges of minimum diameter $d_b = 0.15D$. The upper limit of the grain volume fraction in the FCC lattice of hard spheres is 26%. An amorphous silica was deposited on the inner surface of opal voids thus reducing the free volume down to 13%. Further reduction of porosity was achieved by coating opal voids with 34 monolayers of TiO_2 (O34-sample). The set of O47-samples was prepared by coating the opal with TiO_2 — from 0 (O47.1) to 27 monolayers (O47.2) and to 54 monolayers (O47.3). Effectively, diameters of voids were, approximately, as $d_O = 95$ (90; 80; 60) nm, $d_T = 55$ (50; 40; 30) nm and $d_b = 35$ (30; 25; 20) nm for the O47.1, O47.2, O47.3 and O34 samples, respectively, as defined from the optical Bragg diffraction.

In Fig. 1 the $R(T)$ curves for investigated samples are shown in the vicinity of the superconducting transition. The critical temperatures of superconducting (SC) transition T_c exceed sufficiently $T_c = 3.41$ K of the bulk indium. The increase of the above the bulk value correlates with the reduction of the volume fraction occupied by the In network in the opal. Assuming that the superconductivity nucleates at the narrowest part of the superconductor, the onsets of the resistance drop correspond the SC fluctuations in intergrain bridges. The "average" diameter of the In wireframe can be figured out with the empirical expression $T_c = 3.41 + 5.1/d$ [d in nm] [4]. The value $d = 18$ nm for O34 gives the estimate of

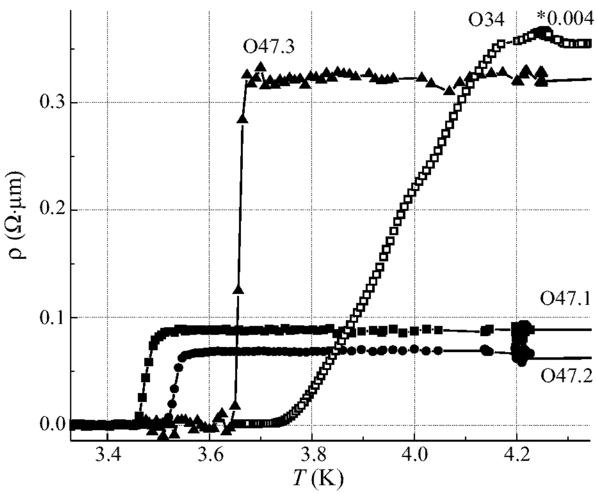

Fig. 1. Temperature dependencies of resistivity at low temperature for O47.1, O47.2, O47.3 and O34 samples (the values of resistivity for O34 sample are divided by 100).

the cross-size of the metal inclusion at the point where the SC spreads throughout the In wireframe as a whole, moreover this result is consistent with SEM data.

Resistivity curves in the temperature range from 300 K to Helium 4 temperatures are shown in Fig. 2 for all studied samples. The overall tendency is the decrease of the temperature-related change in the resistance with the decrease of the wireframe volume fraction, that is likely due to limiting the mean free path of electrons by scattering on grain boundaries rather than on phonons. $H_0(T)$ dependences were extracted from magnetoresistance curves, which are shown in the Fig. 3. The critical magnetic field H_0 is defined as the transition from the SC to the resistive state. Note that the $H_0 = 10$ kOe at $T = 1.57$ K exceeds by 35 times the critical field for the bulk In (280 Oe at $T = 0$ K). The SC transition for O34 sample is spread broadly over a field and shows a kink at approximately the midpoint of the transition. Accordingly, critical magnetic fields indicated as H_1 and H_2 (characteristic fields for derivative $\mathrm{d}R/\mathrm{d}H$ maxima) are shown in Fig. 3 for O34-sample. $H_0(T)$ curves follow the quadratic law, which is typical for type II superconductors. In particular, the expression $H_c(T) = H_c(0)(1 - (T/T_c)^2)$ for interconnected superconducting grains, whose size is less than the coherence length and/or the penetration depth, describes well the observed behaviour. From $R(T)$ curves the mean free path and then the coherence length were determined, which values show that the magnetic field penetrates freely through the In-opal nanocomposite. In this case magnetic vortices in the In grain network are effectively circulating supercurrents, which maintain the integrity of the flux quanta in encircled loops. Moreover, the effective diameter of these loops can exceed considerably the size of the minimum lattice-defined loop of $d_{\min} = 98$ nm. With the increase of the external field the effective loop area decreases and approaches $d_{\min}$. Apparently, this field defines the onset of the resistive state H_0. Because the FCC lattice contains loops, which are differently oriented with regard to the external magnetic field, the loops of smaller projected areas withstand the larger fields without switching to the normal state. Due to this effect the spread of the resistive state in $R(H)$ curves is very large. The fine structure of $R(H)$ curves observed in well-ordered samples can be due to the preferential orientation of the loops in the lattice, which refer to the projection of certain lattice planes on the field direction.

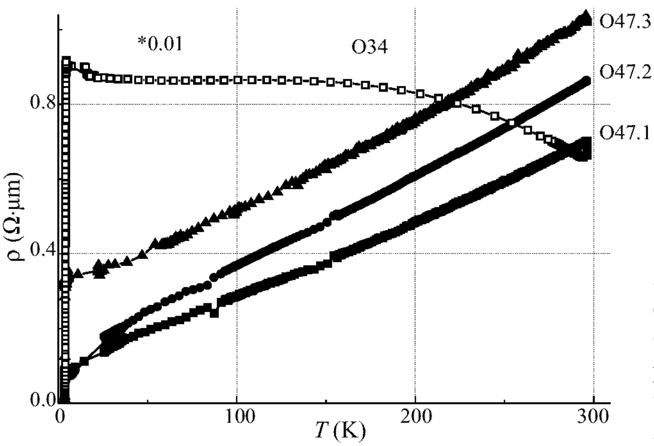

Fig. 2. Temperature dependencies of resistivity for O47.1, O47.2, O47.3 and O34 samples (the values of resistivity for O34 sample are divided by 250).

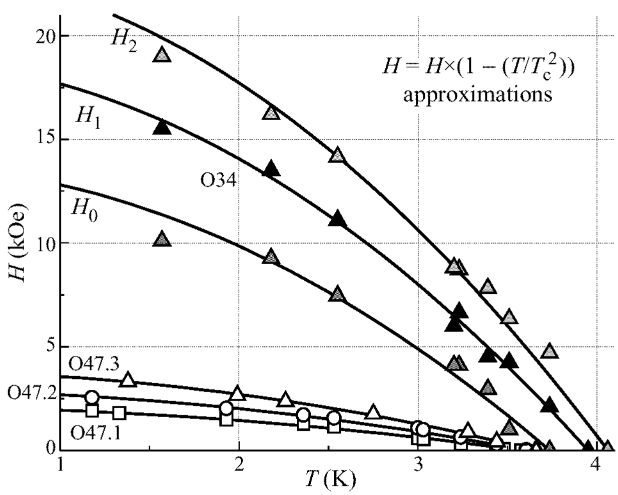

Fig. 3. Temperature dependencies of characteristic magnetic fields: H_0 (determined at the beginning of the resistive state at given T) for O47.1, O47.2, O47.3 and O34 samples; H_1 and H_2 (fields of $\mathrm{d}R/\mathrm{d}H$ maxima) for O34 sample. Solid lines are the $H(T) = H(0)(1 - (T/T_c)^2)$ approximations.

2. Conclusions

The type II like superconducting transition has been observed in the in the regular lattice of interconnected In grains in the opal template. Effectively, this material is nanosize wire mesh made from type I superconductor. With the decrease of the cross-section of In component in the metal-dielectric nanocomposite the increase of the critical magnetic field was observed. The observed relation between the critical field and the effective thickness of In nanostructures correlates with the observed flattening of the $R(T)$ dependence.

Acknowledgements

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